INFILTRATION RATES OF GREEN INFRASTRUCTURE CURB-CUT BASINS: FINDING BALANCE BETWEEN FUNCTION AND AESTHETIC

by

Samantha Swartz

A Thesis Submitted to the Faculty of the

DEPARTMENT HYDROLOGY AND ATMOSPHERIC SCIENCES

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

WITH A MAJOR IN HYDROLOGY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2019

THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Master's Committee, we certify that we have read the thesis prepared by Samantha Swartz, titled *Infiltration rates of green infrastructure curb-cut basins: finding balance between function and aesthetic*, and recommend that it be accepted as fulfilling the thesis requirement for the Master's Degree.

Date: 5/2/19

Paul "Ty" A. Ferré

Date: 5/2/19

Edella Schlager

Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to the Graduate College.

I hereby certify that I have read this thesis prepared under my direction and recommend that it be accepted as fulfilling the Master's requirement.

Date: 5/8/19

Thomas Meixner
Master's Thesis Committee Chair
Department of Hydrology and Atmospheric Sciences

Table of Contents

I. List of Figures

II. Abstract

In arid regions, sustainable water management is critical for a future facing resource scarcity. The city of Tucson, Arizona has implemented green infrastructure designs along streets and right-of-way areas in order to collect the untapped resource of stormwater. Neighborhood-scale green infrastructure projects, in the form of curb-cuts connected to rainwater harvesting basins, successfully capture polluted runoff and create appreciable green spaces. However, after nearly a decade, some neighborhood green infrastructure basins appear actively cared for, while others appear highly degraded, as maintenance has been left to nearby homeowners. This research assesses how maintenance may influence the performance of Tucson's neighborhood green infrastructure, and what maintenance techniques may or may not be necessary. Infiltration rates, measured with a soil corer air permeameter, serves as a metric for basin function, while a qualitative evaluation of the basin's appearance gauges the apparent care. The results found neighborhood curb-cut basins in poor condition have a statistically significant increase in average saturated hydraulic conductivity of the soil. Overall, the drainage of well-maintained basins underperformed relative to neglected basins. Traditional maintenance of curb-cut basins may be unnecessary for the effective infiltration of stormwater runoff. To further support soil structure and permeability, design recommendations include increasing organic mulch and vegetation density. The aesthetics of non-maintained curb-cut basins appear to be problematic for homeowners who deem the neglected basin to be an eyesore. Community engagement strategies that encourage cooperative neighborhood management may improve the aesthetic value of curb-cut basins. This research provides recommendations for neighborhood green infrastructure maintenance and outreach that supports both satisfactory infiltration rates and curbside appeal.

III. Introduction

This research focuses on the topic of green infrastructure and how long-term maintenance strategies may affect the function of neighborhood curb-cut basins. Green infrastructure are city-wide designs that mimic natural watersheds in urban areas. The designs direct excess water into vegetated areas in order to reduce urban runoff, improve water quality, and prevent flooding downstream. Green infrastructure (GI) comes in many forms and sizes, from modest street-side basins to connected washes at the catchment-scale; however, they are all constructed with the intent to capture and filter rainwater in localized areas of soil and vegetation. Common forms of GI include retention basins, bioswales, rain gardens, living roofs, chicanes, permeable pavement, preserved washes, among many others. Interest in metropolitan greenspaces began as urban populations became increasingly dense. In 1994, a Floridian governor coined the term “green infrastructure” after referring to areas of “strategically planned and managed network of natural land” (Hufnagel and Rattle, 2014). Currently, the widely-accepted definition of GI includes the incorporation of native species and critical ecological services for supporting water and air quality in urban centers.

The GI studied in this project are known as rainwater harvesting curb-cut basins. They are neighborhood-scale GI, meaning they are typically built alongside residential streets and sidewalks in right-of-way areas. They reduce flooding by capturing water flowing down the street and letting it soak into vegetated basins. Capturing stormwater before it accumulates downstream has been shown to have substantial benefits. Hufnagel and Rattle (2014) state that GI basins prevent street containments like motor oil or pesticides from concentrating in our waterways, which can lead to a large increase in water treatment costs. GI projects in Seattle, Washington have indicated that neighborhood curb-cut basins significantly improve downstream water quality (Matsuno and Chiu, 2010). Additionally, many researchers extoll GI for its community benefits, such as improved property value, cooler temperatures, air pollution scrubbing, and energy-savings (Coutts and Hahn, 2015), (Hufnagel and Rattle, 2014), (Pennypacker, 2015). However, GI’s high capital costs dampen the momentum necessary for them to be fully incorporated in urban areas (Liptan and Santen, 2017). One bioretention basin in Tucson can cost between two and four thousand dollars (“Triple Bottom Line”, 2018).

In a 2016 report from the U.S. Environmental Protection Agency (2016a), they state “operation and maintenance is a challenge that when not addressed properly can lead to failure of green infrastructure and high costs associated with restoration” (46). The EPA’s report also acknowledges that “limited research is available” when it comes to how regular upkeep impacts the basin performance (2016a). The long-term maintenance plans of GI are undeniably necessary; many of GI’s primary benefits are dispersed over many years. “Without good data on costs of operations, and good policies regarding maintenance, GI can get a bad rap” (Liptan and

Santen, 2017). Cities discouraged by the high initial price tag require information on whether or not maintenance costs will accumulate over time. This research seeks to address those concerns. Rainwater harvesting curb-cut basins in residential neighborhoods were studied to determine if long-term maintenance is needed in order for the basins to function as intended.

Each GI site location was placed into a condition category based on factors contributing to overall appearance. The observed condition of the basin served as a proxy to estimate the level of volunteered maintenance from nearby residents. This qualitative assessment considered the presence of trash, presence of weeds, vegetation health, and inlet/outlet clogging, among others. The metric used to evaluate a GI basin's ability to reduce stormwater runoff was the permeability of the soil. A basin with a higher saturated hydraulic conductivity (Ks) can capture and infiltrate more rainwater than a clogged basin with low hydraulic conductivity. Traditional hydraulic conductivity measurements performed in the field can be tedious and time-consuming, so an indirect measurement was taken. A soil corer air permeameter (SCAP) was used to estimate the air permeability of each basin. This instrument was chosen because rapid measurements can be taken in situ, without altering the soil structure. Under ideal conditions, air and water permeability are considered equal, as they both depend on intrinsic soil characteristics such as the pore shape, size, distribution (Chief, 2007). Under a given set of assumptions, air permeability and Ks can be related to each other through a log-linear correlation, (Loll et al., 1999). Soil core samples were collected and falling head testing was performed to calibrate the fitting parameters of the log-linear relationship between air permeability and saturated hydraulic conductivity. The resulting infiltration rates provide insight about a GI basin's water-harvesting ability. The two variables of observed basin condition and soil permeability were compared to determine if a correlation exists between a basin's apparent maintenance and its ability to infiltrate water. I hypothesized that: 1) There is a relationship between apparent homeowner maintenance and the infiltration rates of GI basins, and 2) higher infiltration rates will coincide with well-maintained basins.

The results of this research were unexpected. The measurements showed an inverse of the proposed hypothesis – neglected basins had consistently higher infiltration rates than basins which appeared well-maintained. From a hydrological standpoint, the neighborhood-scale curb-cut basins appear to be a success. Almost every basin in this study demonstrated satisfactory drainage, which suggests little to no oversight is needed for successful stormwater capture and infiltration. However, the basins with the highest infiltration rates often had the worst appearance. This result suggests an apparent trade-off between the function of the GI basin and its aesthetic value. I interreacted with neighbors who were vocal in their disapproval of overgrown, weed-filled basins, and expressed a desire to block the curb-cut and fill in the basin. This presented a new question about the long-term maintenance needs of neighborhood GI: how can both function and curbside appeal be preserved to maximize GI benefits? The appearance of a GI basin can be critical for encouraging care and attention from nearby homeowners. Later in this paper, I will recommend approaches for motivating homeowners to incorporate GI into their own yardwork, to support both the aesthetic and function of the GI basin. The management recommendations stem from a social perspective of collaborative governance. Green infrastructure is a public good, and maximizing the indirect benefits requires an understanding of social norms and effective collaborative behavior for sustaining an environmental resource. Different community engagement strategies may improve the neighborhood GI's vegetation health and curbside appeal, which would aid the curb-cut basins in reaching their full, intended potential.

IV. Literature Review

During the last two decades, urban areas began re-evaluating how they manage precipitation events. As traditional gray infrastructure – such as pipes, holding tanks, and conveyance channels - become overburdened by rapid growth in population density, GI offers a simple, flexible solution. These novel designs take polluted urban runoff and apply it to a widely beneficial and sustainable use. Instead of viewing rainwater as an irritating inconvenience, many city planners have perceived an untapped resource. In an era of changing weather patterns, booming urban centers, and limited potable water, it's imperative to plan for a future of scarcity. Green infrastructure reflects that ideology. It can alleviate many metropolitan concerns like stormwater contamination, flood damage, and urban heat island effect. There is ample research of GI case studies, and the results are promising enough to spur continued attention into their application and potential (Canfield, 2017), (Cook, 2016), (Matsuno and Chiu, 2010). Below are summaries of the many direct and indirect benefits of green infrastructure, so that the overall value of GI can be placed in context. When considering the potential operation and maintenance costs of GI, it's essential to keep in mind the rewards.

IV.I Water Quality & Flood Control

In dense urban centers, rain events create a host of management problems. Paved ground and building rooftops generate an enormous amount of runoff, and large storm events are a challenge for city planners. The traditional method of handling excess water involves diverting it into pipes, sewers, and holding tanks. These concrete conveyance systems are colloquially known as gray infrastructure. Conversely, green infrastructure follows a more adaptive approach by mimicking natural hydraulic cycles. The environment has a phenomenal capacity to slow flowing water, dissipate the excess energy, and allow the water to soak in. Researchers from the Water Environment Federation found that a forest will soak up almost two inches of precipitation before water begins to run off (Hinds and Beezhold, 2014). On the other hand, cities lined with concrete and asphalt experience significantly decreased infiltration, and almost all rainfall turns to surface runoff. Over impervious surfaces, like parking lots, roadways, and commercial complexes, as little as 0.1 inches of rain can produce eleven cubic meters of surface runoff (Hufnagel and Rattle, 2014). This also presents a water quality issue. As urban runoff flows through a city, it accumulates garbage, motor oils, heavy metals, fertilizers, pesticides, pathogens, and sediments (MacAdam, 2012.), ("Triple Bottom Line", 2018). This pollution creates an enormous burden on ecosystems and water treatment plants downstream of city streets. Hufnagel and Rattle (2014) report that the extra expense and energy needed to move and treat contaminated stormwater is an additional financial burden on small city budgets.

In the 1980s, the Environmental Protection Agency began monitoring the water quality in urban runoff in the Nationwide Urban Runoff Program (NURP). They found that, "storm water was indeed a significant contributor of nonpoint source pollutants in U.S. waters and should therefore be managed to the maximum extent practicable" (Liptan and Santen, 2017). This can be a public health concern. Even runoff from small rainstorm events can result in a surge of highly contaminated stormwater. The City of Seattle experienced this issue frequently. In 2001, the city began the SEA Streets project which installed bioswale basins and curb-cuts along dozens of roadways in residential neighborhoods inflicted with serious flooding issues. The goal was to protect endangered salmon populations from the massive pollutant loads being dumped into Puget Sound after every storm (Matsuno and Chiu, 2010). The pilot installations were successful in many ways. The city of Seattle determined GI basins to be highly cost effective compared to traditional holding tanks and underground piping. Furthermore, after the installation and establishment of GI, they found "the transmission of pollutants through stormwater runoff was reduced by 98%" (Matsuno and Chiu, 2010). Neighborhood beautification was an additional benefit; living in an area with curb-cuts and bioswales became highly desirable. The Harvard Report on Conservation Innovation reported that their neighborhood GI designs were significant, effective, and transferable. The University of Washington applied rigorous, quantitative research methods to ensure the outcomes of the SEA Streets project were monitored and could be easily transplanted in other cities. Their published work predicts that natural drainage systems will improve over time as the vegetation takes root, stabilizing the soil, and increasing the overall retention and infiltration rate of the system (Matsuno and Chiu, 2010).

IV.II Indirect Benefits

Another widely touted benefit of green infrastructure is the mitigation of the urban heat island effect. Human development in large population centers retain large amounts of radiation that can warm "air temperatures as much as 22˚ F compared to less developed areas nearby" (Hufnagel and Rattle, 2014). Black roadways and rooftops are main contributors of this effect. Green spaces, in the form of parks, gardens, washes, or GI, can absorb radiation, provide shade, and lower surrounding air temperatures. Large, healthy trees significantly reduce the ambient temperature and cool the air through evapotranspiration (Coutts and Hahn, 2015). Greenspaces near buildings can also reduce the energy costs needed to heat and cool the building (Hufnagel and Rattle, 2014). Most importantly, this benefit can span several generations. Coutts and Hahn (2015) state that projected local temperature increases over the next 65 years could be essentially negated under the current efforts to expand urban tree canopies.

An understated benefit of green infrastructure are the subtle effects on human health. From an ecological perspective, a healthy environment is indispensable for human well-being. However, the natural environment is often ignored or overlooked despite being foundational to public health. Authors Coutts and Hahn (2015) wrote a literature review of all the "empirically-supported human health benefits of GI". For example, a thorough study done over a number of dense Chinese cities found that trees were effective sources air pollution abatement. Tree leaves collect air particulates on their surface and serve to scrub the air clean of fine contaminate matter. In the US cities of Atlanta and Houston, trees removed 3.2 and 4.7 tons of fine particulates per square mile annually (Coutts and Hahn, 2015). Trees have also been shown to remove noxious gases, such as ozone, carbon monoxide, and nitrogen oxides. Nearby forests, parks, and protected watersheds can reduce the number of people experiencing acute respiratory symptoms due to air pollution. Additionally, a relationship exists between physical activity and access to green spaces (Coutts and Hahn, 2015). If green environments are nearby and easily accessible, a neighborhood is likely to report higher frequencies of physical activity, such as walking or running. Exposure to greenspaces can reduce stress and stress-related illnesses, as well as create feelings of peace and well-being (Coutts and Hahn, 2015**)**. Greenery is often a pleasant and welcomed element in locations dominated by concrete and asphalt.

IV.III Economic Benefits

Another essential element of green infrastructure is the long-term economic value. Pima County completed a study called the Action Plan for Water Sustainability (Impact Infrastructure, 2014). A business analytics tool was employed to quantify and monetize all GI benefits. The report cited green infrastructure as the most cost-effective solution, due to several benefits spanning the GI's entire lifetime, including "increased retail sales, rents, and property values; energy and water savings; reduced gray infrastructure costs; higher rates of worker happiness and productivity, and lower crime rates" (Impact Infrastructure, 2014). Pima County is not the only entity to draw this conclusion about the economic value of GI. Seattle Public Utilities (2018) conducted GI case studies by analyzing curb-cut designs installed in the early 2000s. They found GI installations "costs 25% less than traditional roadside stormwater systems, because reducing runoff at the source reduces the need to build additional pipes and holding tanks" (Matsuno and Chiu, 2010). Instead, natural vegetated basins can function as spongy "holding tanks" for excess stormwater runoff.

IV.IV Local Green Infrastructure Practices

Over the years, the city of Tucson and local environmental non-profits have been honing their stormwater management practices. In 2013, the director of the Engineering Division for the Department of Transportation signed active practice guidelines called Green Streets for the use of GI in roadways (Wittwer, 2013). The goal was to incorporate GI designs for all new projects, as much as possible. The primary purpose of the guidelines are to build basins that reduce stormwater flooding and capture, at minimum, the first half inch of rain. Detaining the initial half inch, or the "first flush", of the rainstorm can be critical for public health. Watershed Management Group reports the first flush harbors the most urban contaminants, such as oil, grease, brake dust, heavy metals, animal feces, and herbicides (MacAdam, 2012). Furthermore, the Department of Transportation requires that GI basins be fully drained 24 hours after a rainstorm event, allow a pooling depth of eight inches, and "encourage a maximum dispersal and infiltration of stormwater across the pervious area" (Wittwer, 2013). The second priority of Green Streets is to increase the urban tree canopy. At minimum, a tree should cover 25% of the "Tree Canopy Area", or the area where trees can be planted without obstruction to driver visibility or utilities. Trees are strategically placed to shade sidewalks and buildings. Bushes and shrubs should also cover 25% of the groundcover in a basin (Wittwer, 2013). The Department of Transportation notes that these are minimum requirements, and efforts should be made to exceed the given guidelines.

In 2016, Tucson's mayor approved the Neighborhood Scale Stormwater Harvesting grant program. The environmental non-profit Tucson Clean & Beautiful is contracted to assist neighborhoods with the application process and implementation of community GI installations (Tucson Clean and Beautiful, 2017). The Water Conservation Fee funds the administrative oversight and contractors selected for the projects. This grant program focuses on low impact development, or passive rainwater harvesting designs. Once again, the primary goal of the project is to mitigate stormwater flooding in neighborhood. Nevertheless, Tucson Clean and Beautiful is clear in listing the additional GI benefits: "Neighborhoods benefit from harvesting stormwater when projects include trees and vegetation. Communities are cooler. Recreation is encouraged. Property values increase. Air quality improves. Trees create a sense of place" (Tucson Clean and Beautiful, 2017).

Often, the unspecified costs of green infrastructure hinder the advancement in city planning (Pennypacker, 2015), (Ahiablame et al., 2012). Securing long-term funding for any project proves to be a challenge, whether the infrastructure is gray or green. While the architecture authors of *Artful Rainwater Design* agree that most GI projects have more return dollar for dollar, simple maintenance still needs a clear plan and tenable funding. When maintenance is overlooked, there is the risk of lowering the performance of the system (Pennypacker, 2015). Unfortunately for policy makers, “the literature currently lacks comprehensive research on how performance relates to operation and maintenance” (US EPA, 2016a). Uncertainty about the spatial and temporal changes to GI effectiveness instills wide-spread reluctance (Ahiablame et al., 2012). This research seeks to address the management knowledge gap of how long-term maintenance practices impact GI basin function.

V. Methods

This study was performed in five neighborhoods in Tucson, Arizona (Figure1). Three neighborhoods are classified as National Register Historic Districts, and they are situated near parks and biking routes which encourage pedestrian travel. These neighborhoods were retrofitted with green infrastructure approximately six to eleven years ago. One neighborhood had a mix of basins projects, ranging from four to ten years in age. The fifth neighborhood had twelve curb-cuts installed in the spring of 2018 and provides a contrast to the older basins. The GI basins were placed in neighborhoods with the purpose of reducing stormwater flooding, providing urban tree canopy, and improving walkability. A total of 88 basins were measured, with a sample of 12 to 22 curb-cut basins from each neighborhood. The location of each basin measured in this study is seen in Figure 2.

Figure 1 - Five neighborhoods of study in Tucson, Arizona: Feldman’s (purple), Jefferson Park (green), Rincon Heights (red), Blenman Elm (blue), Garden District (brown).

V.I The Neighborhoods

Jefferson Park: The first three curb-cuts were installed in 2009. Two additional sets of three basins were placed in 2011 and 2012. The following year, a non-profit organization Conserve to Enhance won a grant to install seven additional curb-cut basins (Conserve2Enhance, 2018). This brought the neighborhood total to 16 GI basins. Owing to its proximity to campus, this neighborhood is largely rental homes with high pedestrian and bike traffic.

Rincon Heights: A total of 18 curb cut sites were installed between 2009 – 2010 by the Watershed Management Group. This neighborhood is within High School Wash and has been the focus of many GI pilot studies. Directly south of the University of Arizona campus, this area is primarily composed of rental homes and experiences a high amount of pedestrian traffic to and from campus.

Blenman Elm: In 2008, 28 curb cuts were installed along Treat Avenue - the central bike corridor of this neighborhood. This section of Treat Ave is a paved over wash and experiences frequent flooding. The neighborhood received grant funding and a permit for 8 additional curb cuts in 2011 and 2012. Several schools and parks are in close proximity. This area has more permanent residents than the campus neighborhoods.

Feldman's: This neighborhood is split between two washes, the Rio Mabel and the Bronx Wash. 4th Ave runs down the center and has relatively steep street gradients, making it prone to flooding. 25 basins were placed in the Bronx Wash 10 -15 years ago. This is an approximate time-framed based on the curb-cut in an original, small circular shape. In 2015, Conserve to Enhance received funding to place 16 more basins within the Rio Mabel wash. This study examined 22 of the 41 total basins.

Garden District: This area is characterized by an active neighborhood association, and in 2018, they received the grant to install a series of GI designs along Justin Lane, which included 12 curb-cut basins. While the four previous neighborhoods installed curb-cuts similar to Figure 3 below, the Garden District project differs by adding approximately three inches of woodchip mulch in each basin. The vegetation is also more limited- instead of several native plants, they limited the basins to one tree and one small plant each.

Figure 2 - (a-e). GI curb-cut basin locations in each neighborhood. Feldman's (a) with 22 basins. Jefferson Park (b) with 16 basins. Blenman Elm (c) with 18 basins. Rincon Heights (d) with 20 basins. Garden District with 12 basins (e).

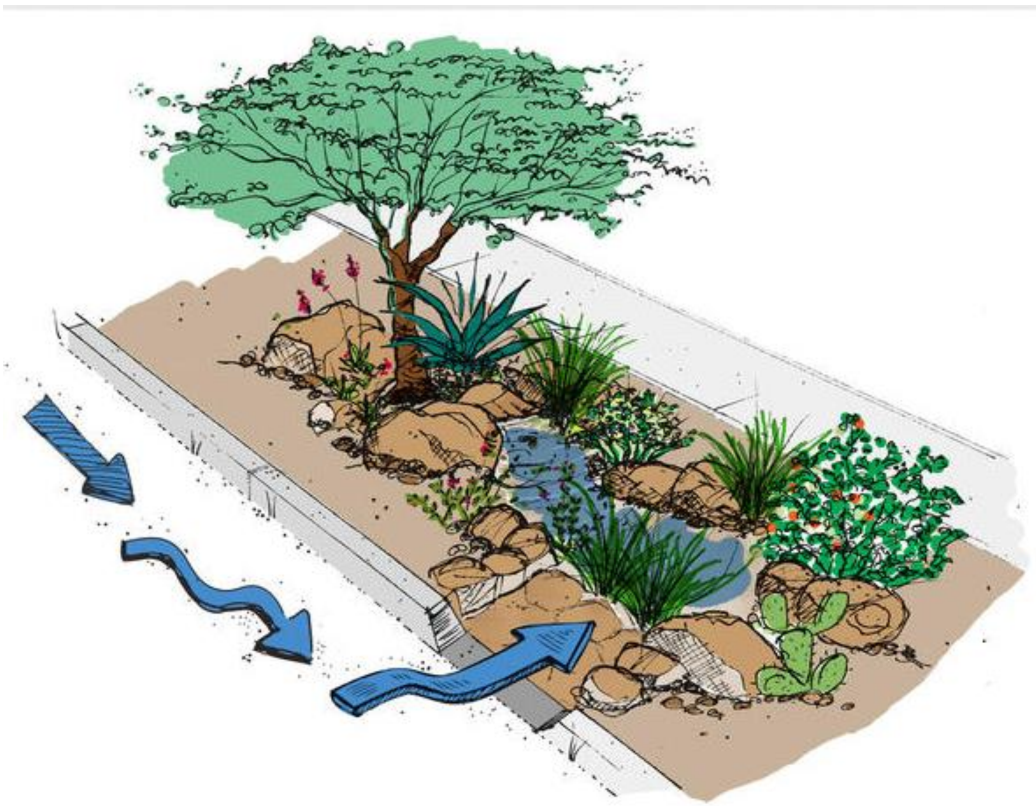


Figure 3 - Watershed Management Group's concept design for a curb-cut basin (MacAdam 2010).

The construction of all 88 basins in this study was facilitated by environmental non-profits following established engineering guidelines set forth by Tucson's Department of Transportation (Wittwer, 2013). With the exception of the Garden District, all well-maintained basins look similar to the Watershed Management Group's concept design (Figure 3). For this study, it is assumed all basins matched Figure 3's design at the time of installation. Each site is defined as a single curb-cut feeding between one to three shallow basins with native vegetation. The sites were originally constructed with a level, medium-grained sandy bottom. Cobble-sized rocks line the inlet and outer edge of the GI site to prevent soil erosion. Desert-tolerant trees were planted at the end of each basin, along with a small assortment of native shrubs and cacti. The vegetation consists of desert willow, palo verde, or mesquite trees accompanied smaller plants such as creosote bush, desert broom, ocotillo, century agave, desert hackberry, among others. There are some exceptions to Figure 3's design. The oldest basins are more rounded, rather than L-shaped, and the curb-cuts are small, circular holes approximately the size of a pringles can. These small curb-cuts can easily become clogged, and each subsequent generation of curb-cuts gets a little wider. The Garden District incorporates woodchip mulch and less vegetation. Figures 4 and 5 below illustrate examples of well-maintained GI versus neglected basins.

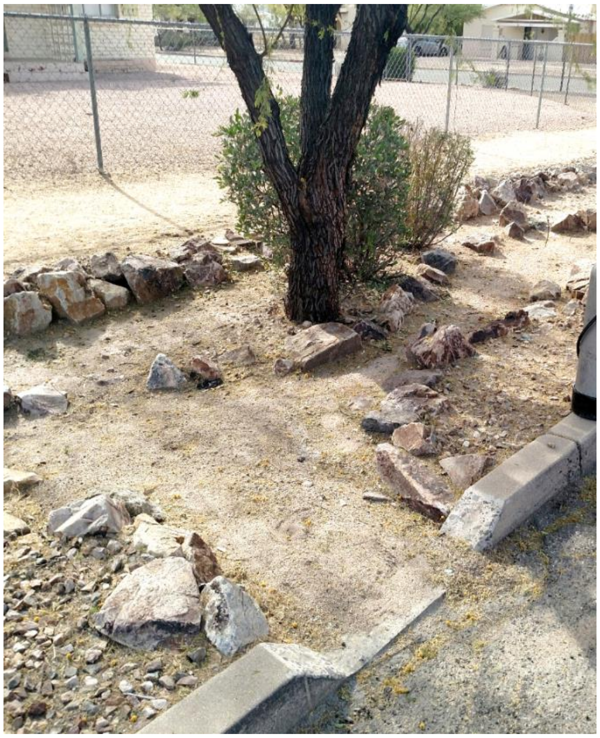


Figure 7 – Basin in great condition, Appears well-maintained.

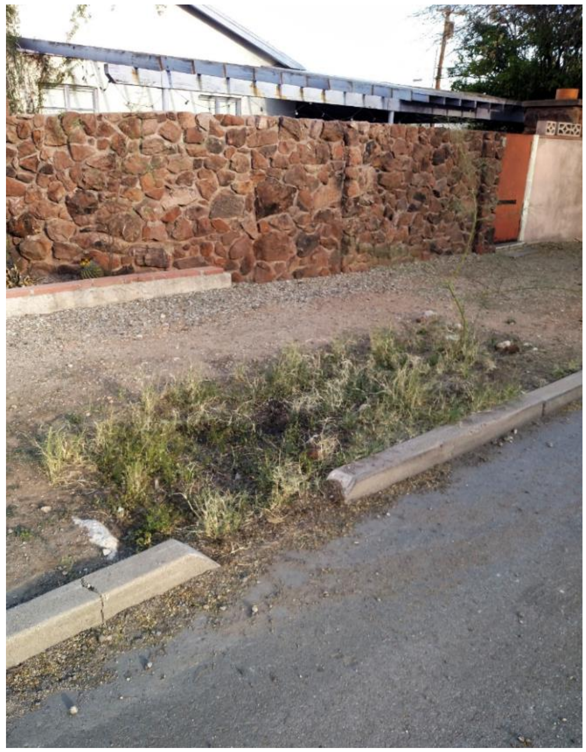


Figure 4 – Basin in poor condition, Appears neglected.

V.II Basin Assessment

The first step in collecting data for this project was assessing the overall appearance of each basin. The basin condition corresponds with the apparent amount of maintenance each basin received from a nearby homeowner. A qualitative metric of the assessment is outlined (Table 1). A “great” condition basin has evidence of routine care and upkeep; this includes pulling weeds, picking up trash, trimming plants, clearing inlet blockages, and keeping the cobble stone borders in place. A “poor” condition basin shows signs of neglect, primarily through the amount of trash, presence of weeds, accumulated organic litter, or dismantled border. If a nearby resident ignores large pieces of garbage or allows overgrown weeds throughout the basin, it is unlikely they volunteer any level of landscaping care. Basins in neighborhoods with high pedestrian traffic tended to have higher amounts of litter along sidewalks and gutters.

Metric for assessing level of homeowner maintenance based on appearance.

Category	Basin Condition	Description
1	Great Appears well-maintained	• Well-defined basin borders • Little to no trash, dead plant debris • Trimmed bushes, evidence of pruned trees • Large, healthy, blooming plants • Inlet clear and free of obstructions
2	Fair Appears somewhat maintained	• Basin borders are mostly defined • Low to moderate presence of trash • Small amount of weed growth, plant debris • Mixed plant health – some struggling, some flourishing
3	Poor Appears neglected, dilapidated	• Washed-out, basin borders are unclear • Heavy presence of trash • Moderate weed growth, accumulated plant debris • Poor plant health – dead or struggling • Inlet blocked or clogged

Every basin was given a unique name based on its neighborhood and street location. Photographs available at https://repository.arizona.edu/ document each site location, and include descriptions and classifications based on Table 1. After a qualitative examination, a number from 1-3 was assigned to each basin, based on degree of factors observed. Out of the 88 basins evaluated, 26 were in "great" condition, 37 were in "fair" condition, and 25 were in "poor" condition. At each site, infiltration rates of the soil were measured. The basin condition categories were grouped together to assess whether or not a correlation existed between apparent maintenance and soil permeability. This research began with the hypothesis that basins classified as being in poor condition, absent of maintenance, would have the slowest infiltration rates, while basins in great condition, appearing well-maintained, would have higher permeabilities.

As infiltration rate measurements were collected at each GI basin, a second qualitative assessment was developed. The instrument used for air permeability testing requires a level surface, cleared of sticks, leaves, weeds, and other debris. Some cared-for and manicured basins retained their clear sandy basin bottom, like the concept design (Figure 3). This was labeled Category A, as described in Table 2 below. Some neglected basins had a thick build-up of organic matter that required removal to get to the soil surface. This fell into Category D (Table 2). During later analysis, these basin surface categories became essential for understanding why basins in poor condition consistently had higher infiltration rates than basins in great condition. This unexpected phenomenon will be discussed later.

Table 2: Metric for assessing the surface of the soil in the basin

Category	Basin Surface	Description
A	Sand	• Mostly sandy bottom • Little to no gravel • Little to no leaves, trash, or weeds
B	Sand and gravel mix	• Some bare sand along bottom • Moderate to heavy mix of gravel • Small amounts of leaves/trash/weeds
C	Thin Layer of Debris	• Moderate sand and gravel mix • Small trash presence • Leaves, branches, dead weeds, mesquite pods
D	Thick Layer of Debris	• No sand or gravel seen • Heavy trash presence • Heavy amounts of leaves, branches, dead weeds, mesquite pods, other debris

The third metric of basin assessment examines overall basin function. The permeability of the soil was considered an indication of how well the GI basin captures and infiltrates stormwater. If the infiltration rate is very low, it can be surmised the basin does not harvest rainwater as intended. If the infiltration rate is high, it suggests the basin can successfully drain runoff. While numerous factors can impact the saturated hydraulic conductivity (Ks), the infiltration rate of each basin was compared to the apparent maintenance to determine if a correlation exists. The instrument employed for this data collection is called a soil corer air permeameter. This device utilizes one-dimensional Darcian flow to calculate the air permeability of the soil, which can be used to estimate the intrinsic permeability (k) of the soil.

V.III Instrumentation

A soil corer air permeameter (SCAP) designed for semi-arid climates by Chief et al. (2007) was used to estimate the air permeability of each basin. The theory behind the SCAP is relatively simple. When water moves through unsaturated soil, the transport depends on the amount of soil moisture and the hydraulic conductivity, both as a function of suction head (ψ). Finding an accurate $K(\psi)$ is both tedious and time-consuming, further complicated by the high variability at field scale. However, like the saturated hydraulic conductivity, air permeability depends on the site-specific soil characteristics, such as pore shape, size, distribution, and porosity. These physical soil properties are called the intrinsic permeability. The fundamental idea is that the permeability of a soil matrix, or how well it drains, is independent of the fluid type, so long as the fluid does not interact with the soil in a way that changes the structure (Loll et al. 1999). This implies that when the soil is completely dry, fluids such as air and water could be interchangeable. Additionally, the permeability depends exponentially on the pore-size distribution and how fluid-filled pores are connected. When suction head is low, the largest fluid-filled pores cannot connect, and the hydraulic conductivity decreases accordingly. A large enough suction pressure applied to the soil provides a good insight to the permeability across all soil pore sizes. Prior publications from Chief et al. (2006), Jalbert and Dane (2003), Loll et al. (1999), and Weeks (1978) show consensus that a good correlation exists between a soil's air permeability and its saturated hydraulic conductivity under the right conditions. The SCAP provides an air pressure gradient using steady-state, laminar air flow; this allows for Darcy's Law to be applied. With Darcy's Law, the infiltration rate can be obtained. The main advantage of the SCAP is the speed – once the equipment is in place, the air permeability can be measured in about five minutes. This allows for a greater number of basins that can be studied, compared to more traditional field instrumentation such as single and double-ring infiltrometers.

The field methods protocols for the SCAP were followed as directed by Chief et al. (2006). Measurements were taken at the lowest depression closest to the basin inlet. The soil core barrel was gently tapped into the soil surface using a standard soil core sampling handle. The barrel was placed perpendicular to the soil surface and any horizontal movement during installation was minimized. Once the barrel was placed and the handle removed, soil was gently packed around the inside and outside edges of the barrel to prevent preferential air flow along the barrel sides. A pressurized air tank, flow meter, and manometer were attached to the appropriate locations (Figure 6). Air was released from the air tank and into the soil core until the pressure stabilized, and the flow rate was recorded. Some practice may be necessary for securing the sampling handle to the soil core barrel. If the handle screws on too tightly, the soil can be disturbed during efforts to remove the handle from the soil core barrel. Additionally, if the threading on the soil core barrel is not cleaned of fine dirt and particulates, it can be extremely difficult to unscrew from the handle. Instrument care was particularly important while taking measurements out in the field.

The SCAP works best in soil at field capacity or drier. A complicated relationship develops if soil moisture is present while measuring the air flow. Essentially, with dry soil, only one fluid is moving through the soil matrix. If water is present, two fluids move through the pore space. Additionally, the wetting process can change the soil structure in ways that the air permeability does not properly capture, due to swelling, slaking, or dispersion. Therefore, measurements were only conducted in dry basins. This could be confirmed by taking air flow measurements at three different pressures. If airflow changed linearly with pressure, the soil was considered to be dry. The movement of gas in a non-Darcian way through porous media, or slip-flow, was another potential complication of the air permeability measurements. However, Weeks (1978) showed that slip flow has a significant influence only in soils with high amounts of fine silt or clay particles. The majority of basins contained loose, sandy gravel, so the slip factor was not a concern with these measurements. However, Chief et al. (2006) and Loll et al. (1999) describe unexpected sensitivity in pores larger than 30 micrometers. This required calibration of the log-log linear relationship between water and air permeability.

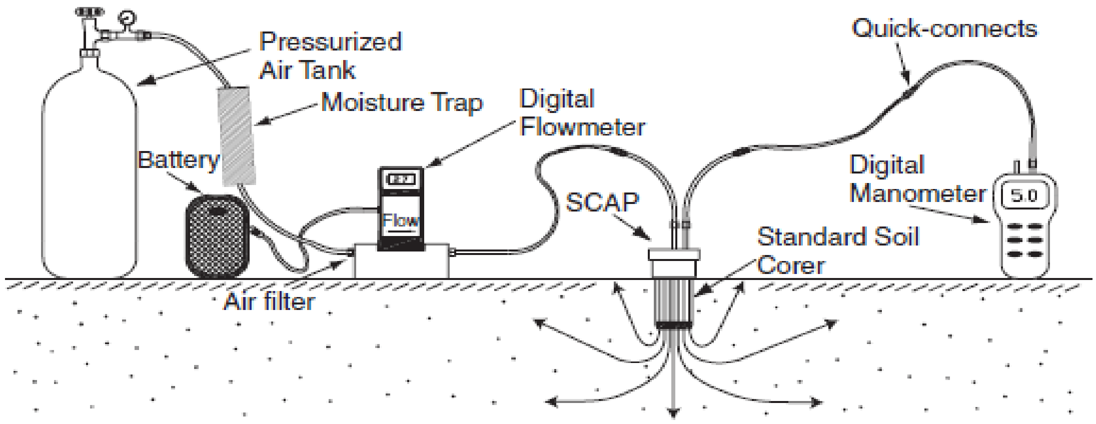


Figure 8 – SCAP instrument set up in the field (Chief et al., 2006).

Provided all the assumptions are met – isotropic conditions, limited clay particles, little to no soil moisture, steady-state air flux – relating air permeability to saturated hydraulic conductivity is a simple process. First, the in situ measurement of air flow is related to the air permeability through the 1D Darcy equation (Chief et al., 2006). The following equation translates the air flux measurement from the SCAP to the air permeability:

$$k_a = \frac{Q\eta}{A}\frac{L}{\Delta P}$$

where k_a is the air permeability, Q is the air flow, η is the dynamic viscosity, L is the length of the soil corer, ΔP is the change in pressure, and A is the cross-sectional area of the soil core. In this case, because measurements were made in the field, a shape factor is needed to correct for divergent flow out of the SCAP endpiece. The divergent air flow is illustrated by the arrows in Figure 6. Jalbert and Dane (2003) discussed the shape factor as a ratio of length between pressure changes and area of the soil core. Developed using the modeling program Hydrus 2D (Simunek et al., 1999), the equation is as follows:

$$A = D(\frac{\pi}{4} + \frac{D}{H})\left(1 + \frac{D}{H}\right)^{-1} \ln(1 + \frac{D}{H})$$

where D is the diameter of the soil corer, and H is the length inserted in the soil (Jalbert and Dane, 2003). Once k_a is calculated using the shape factor, it can give a value of saturated hydraulic conductivity (K_s). Loll et al. (1999) have shown that pressures set between a certain range gives a strong log-linear correlation between k_a and K_s. The equation that relates the two is as follows:

$$\log K_s\ [\log(\mathrm{cm\ min^{-1}})] = 1.27 \log k_a\ [\log(\mathrm{cm^2})] + 14.11$$

The equation above is derived from the average k_a -K_s relationship of nine different soil types. Because of the higher sensitivity of sandy soils to air permeability, Loll et al. (1999) recommends parameterization for a given location. In order to find the site-specific fitting parameters, soil cores were collected at select basins in every neighborhood. In order to obtain a proper comparison, the chosen basins had particularly low or high air flux measurements. Falling head tests were performed on the soil cores in a controlled, laboratory setting. The test measures the soil permeability by timing how long it takes water to flow through a saturated core sample connected to a standpipe. The time starts and ends at predetermined water levels in the standpipe (Head, 1982).

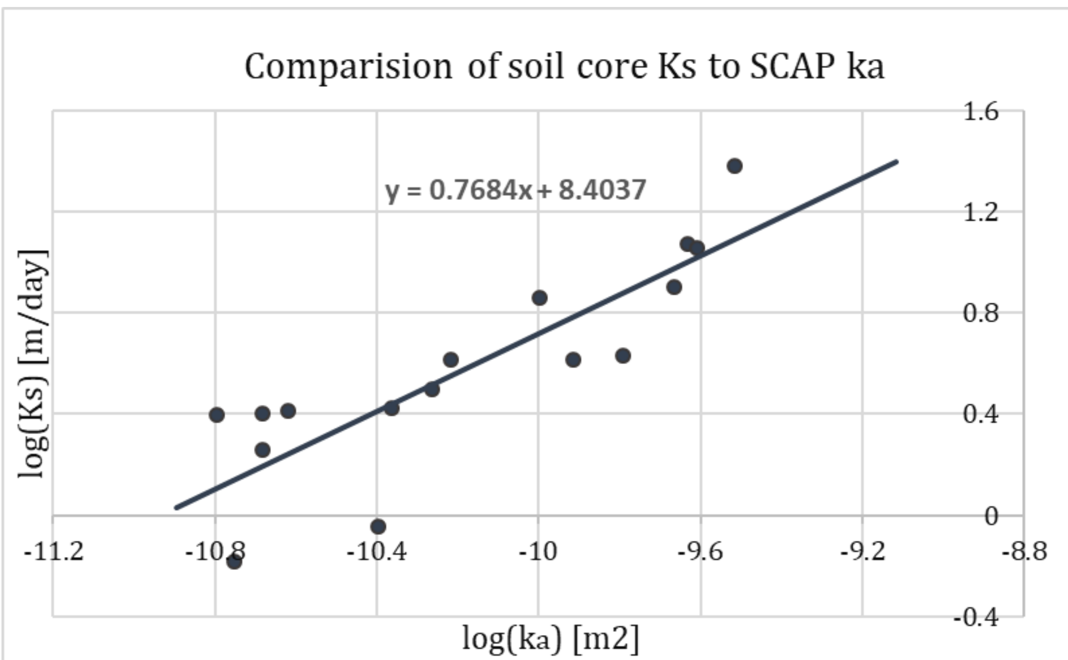


Figure 9 – Parameterization of linear log-log relationship between ka and Ks.

The falling head tests were repeated to characterize any variation. The test failed when variation exceeded 10% (Head, 1982). This produced a saturated hydraulic conductivity value for each of the selected basins. Figure 7 indicates the fitting parameter determination by graphing log K_s against the flied air flow measurements, log k_a.

VI. Results

The results of this research in GI basin maintenance are graphically presented below. Basin condition and the saturated hydraulic conductivity rates in centimeters per minute are compared (Figure 8). The majority of basins in great condition tend to fall below average. Fair condition basins vary widely, but overall, their permeabilities are slightly below average. On the contrary, basins in poor condition, absent of maintenance, tend to have infiltration rates well above average. A F-test and T-test was performed between basins in great and poor condition, to assess whether or not the infiltration rates are from the same population. The variances of the two basin categories were found to be unequal. Similarly, the t-stat was greater than t critical two-tail value, indicting the means of the two infiltration rate populations are unequal. The p-value was well below 0.05, drawing the conclusion that the infiltration rates of basins in great condition versus basins in poor condition are statistically significant.

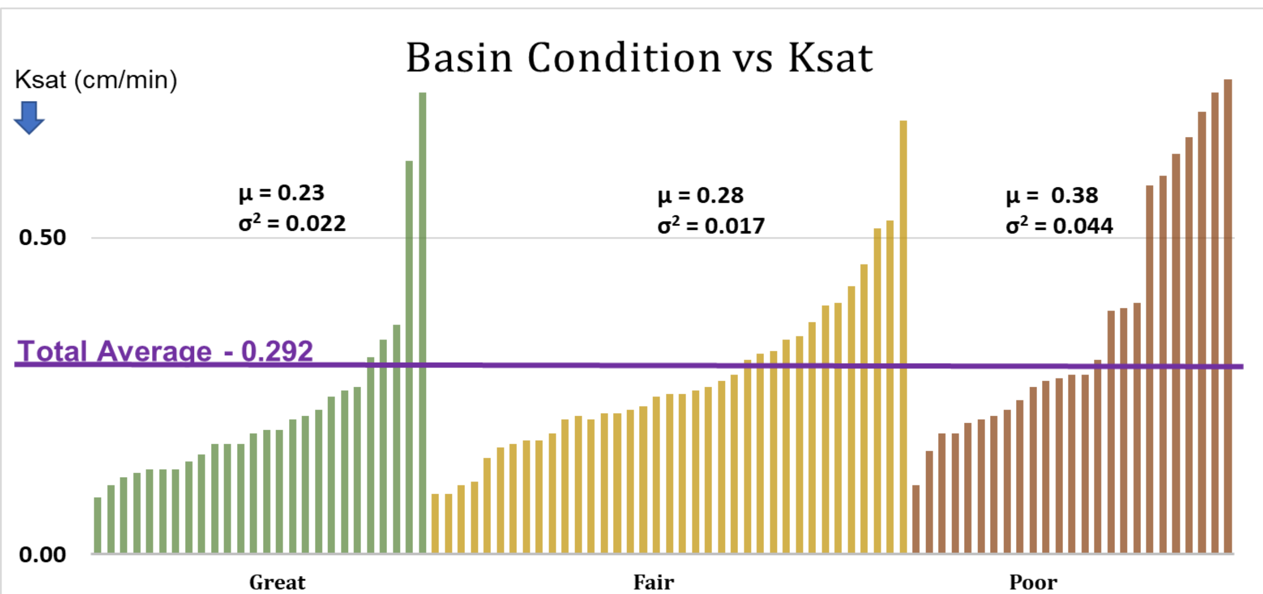


Figure 10 - GI basin infiltration rates sorted into three categories of basin condition based on apparent maintenance level. Labels "μ" and "σ^2" above each condition denote the sample mean and sample variance respectively. The purple line represents the total average K_s for all basins, which equals 0.292 cm/min.

Figure 9 demonstrates the comparison between infiltration rates and the basin surface. This graph demonstrates that the greater amounts of mulch and organic debris corresponds to higher soil permeability. Note that basins that appeared under maintained, in fair and poor condition, tend to have organic debris. Many neglected basins had a build-up of dead weeds, leaves, and seed pods. However, this was not universal. Some poor condition basins had sandy surfaces, and some great condition basins had accumulated organic matter. In particular, the Garden District had several well-maintained, manicured basins with thick layers of woodchip mulch applied to the surface. The B category lacks samples primary due to the difficulty of inserting the SCAP into rock gravel. GI basins where air flow measurements could not be taken were not considered in this study.

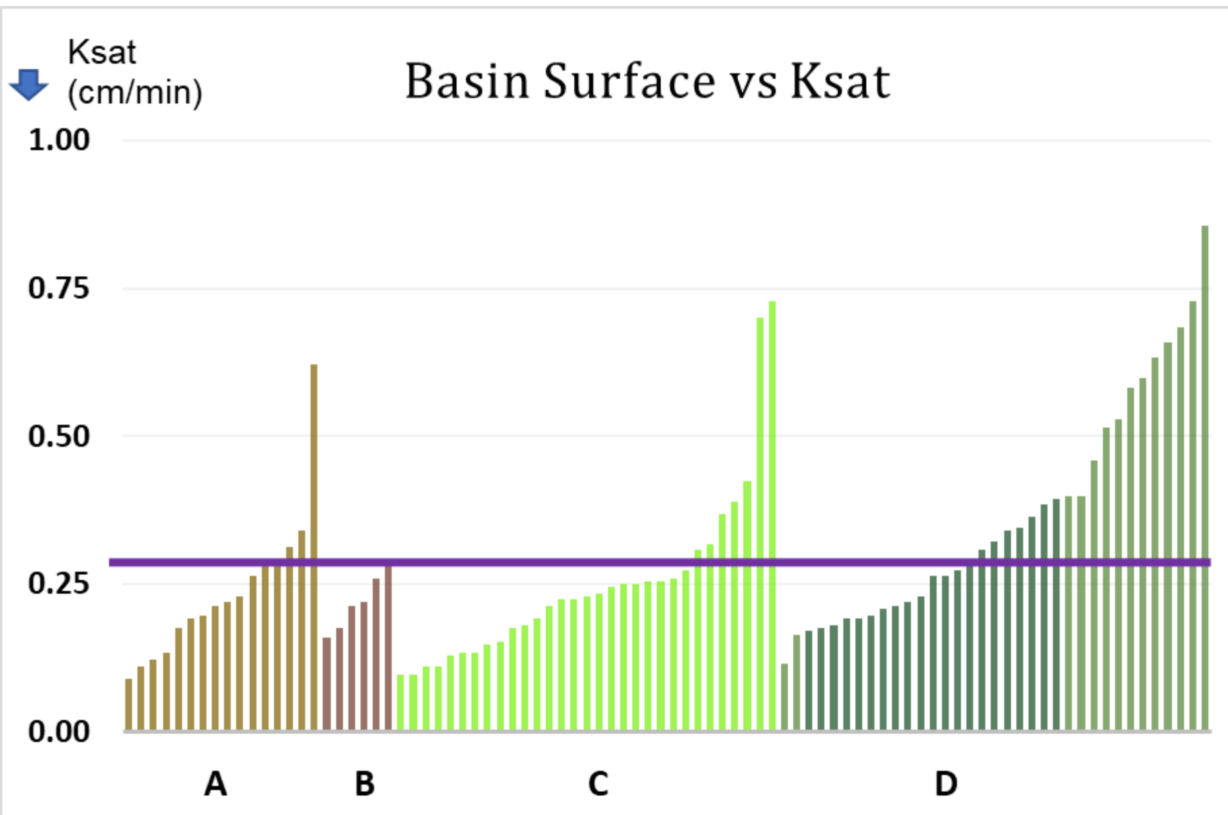
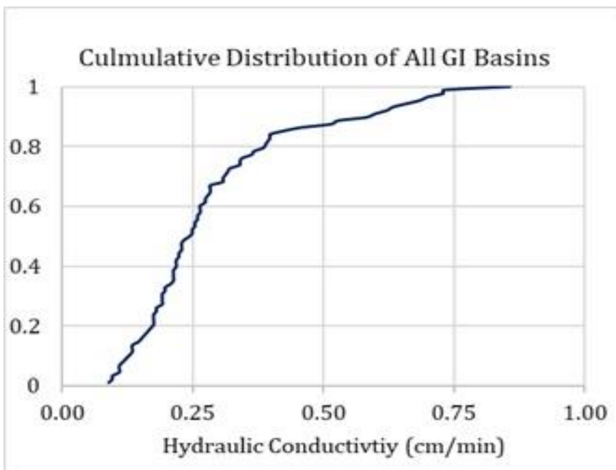
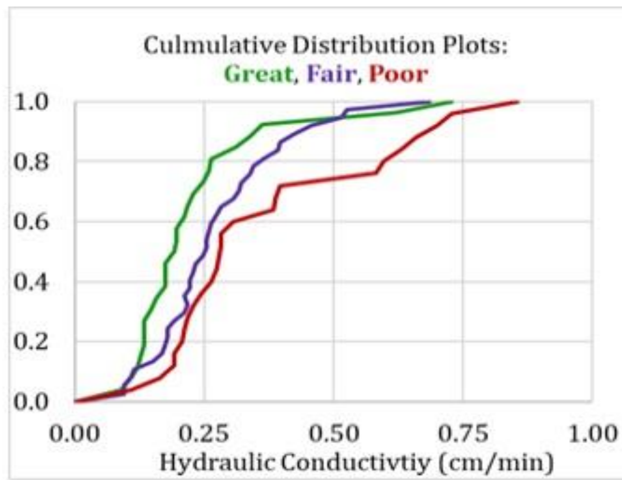


Figure 11 - Basin infiltration rates are compared to categories of top soil condition.
A – sand, B – gravel/sand mixture, C – thin layer of organic litter, D – thick layer of organic litter. The purple line represents the total average K_s for all basins, which equals 0.292 cm/min.

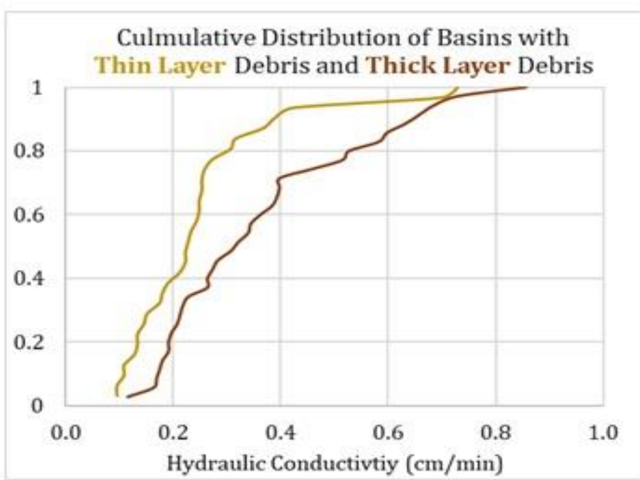
Below, the saturated hydraulic conductivities are visualized through cumulative distribution plots (Figure 10). It's important to note that 65% of basins fall below the total basin average of 0.292 cm/min, and high infiltration rates have a long tail. Neglected basins consistently have higher hydraulic conductivities compared to well-maintained basins (Figure 10b). It appears mulch plays a role in GI basin drainage. A heavy layer of organic matter has a clear increase in infiltration rates compared to basins with small amounts of organic debris (Figure 10c).



(a)



(b)



(c)

Figure 12 (a-c) - All 88 GI basins plotted as a cumulative distribution frequency (10a). GI basin conditions plotted as a cumulative distribution frequency (10b). GI Basins grouped by soil surface category (10c). Only thin layer and thick layer of debris categories are plotted due to sample size.

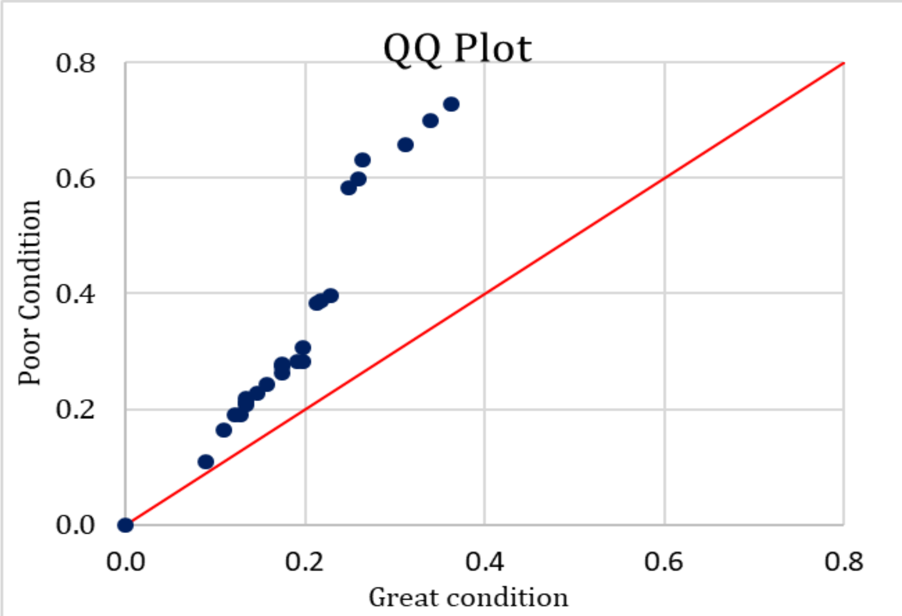


Figure 13 - QQ plot comparing the infiltration rates of basins that appear well-maintained (great condition) and absent of maintenance (poor condition)

The hydraulic conductivity rates of well-maintained, great condition basins and poor condition basins are directly compared in a quantile-quantile probability plot (Figure 11). If both basin categories came from the same population, the points would cluster along the red line, where the two population quantiles align. However, the difference between the two populations is statistically significant. Almost every poor condition basin has higher permeability, and in several instances the hydraulic conductivity is double the rate that of a well-maintained basin.

VII. Discussion

Initially, the results of this project were a surprise. It was hypothesized that maintenance was related to the performance of GI, and well-maintained basins would have higher permeabilities, while neglected basins would have lower permeabilities. This was not the case. Instead, the most derelict basins demonstrated consistently higher saturated hydraulic conductivities. There is a clear shift in the cumulative distribution plots to higher infiltration rates for basins in poor condition, compared to basins that seem to be in great condition (Figure 10b). This is a statistically significant shift in the mean values for populations of neglected basins compared to well-maintained basins. This trend is also confirmed by Figure 11. The infiltration rates of poor condition basins always outperform the rates of great condition basins. In the lower quantiles, the infiltration rates between the two populations are fairly close, differing by approximately 0.05-0.1 cm/min, or 3-6 cm/hour. For higher infiltration rates, poor condition basins are draining between 0.33 – 0.37 cm/min, or 20-22 cm/hour faster than their well-maintained counterparts (Figure 11). This suggests neglected basins capture and drain greater volumes of stormwater runoff. The cumulative distribution plot in Figure 10c may indicate why this phenomena is observed.

Basins in poor condition often had a thick layer of accumulated organic matter. Figure 10c illustrates another clear increase in the hydraulic conductivities between basins classified with a thick layer of organic debris compared to a thin layer of debris. This suggests the build-up of organic matter, such as leaves, sticks, dead weeds or plant debris, plays a role in facilitating soil permeability. In fact, the organic content of soil can support several functions, such as suppling slow-release nutrients, providing food for soil organisms, and culminating stable soil aggregates (Franzluebbers, 2002, Houdeshel et al. 2013). Soil aggregates are when soil particles clump and bind together, reducing erosion and degradation processes. Aggregation in organic rich soil has been shown to increase water infiltration, support soil microbiota, and allow oxygen flow to plant roots (Franzluebbers, 2002). In general, aggregates form a stable soil structure that can allow more drainage. In one study on the effects of field tillage on soil organic content, the infiltration rates tripled when high amounts of organic content and stratification were kept intact (Franzluebbers, 2002).

As a thick layer of organic litter builds up, it has the potential to enrich the local microbiota. Soil biota refers to organisms living in the top soil – bacteria, fungi, earthworms, ants, or plant roots. With suitable soil moisture and temperature, evidence suggests that microorganisms alter soil structure in a way that facilitates better air and water flow through the soil profile (Bronick and Lal, 2005), (Wright and Upadhyaya, 1996). In 1988, Elliot and Coleman documented “strong feedbacks between soil organisms and soil structure” where microbial activity changes the soil structure to improve infiltration. There are a few factors that contribute to this phenomenon. Some fungi and bacteria excrete a microbial extracelluar polymeric substance (EPS) which acts like a hydrophobic slime on soil particles (Morales et al., 2010), (Houdeshel et al., 2013). The hydrophobic compounds change the angle of wettability and keep incoming water in the “center lane” of the pore space. Too much microbial slime from an overactive fungi and other organisms can clog pore space; however, semi-arid environments with irregular water availability limits EPS in a way that can enhance the hydraulic conductivity. Even small amounts of EPS can have significant effects for facilitating vertical water movement (Morales et al., 2010). Soil biota can also increase infiltration rate by creating macropore spaces. The extracellular compounds clump soil particles together, enhancing the aggregation. Arbuscular Mycorrhizal Fungi (AMF), found in most US soils, binds soil together with an adhesive protein during wetting and drying cycles (Wright and Upadhyaya, 1996). According to authors Bronick and Lal (2005), when a soil is stabilized from the formation of new aggregates, the “microbial influence is most pronounced in sandy soils”. Soil biota, fueled by the nutrient recycling of accumulated organic matter, can allow preferential flow paths to form and has the potential to increase drainage in sandy soils.

The effects of soil organic matter and microbiota on the hydraulic conductivity of soil is one possible explanation for the results seen in Figures 10b and 10c. Macropores created by plant root growth could also explain why overgrown, neglected basins have higher infiltration rates than well-maintained basins. In general, the well-maintained basins had clear, sandy soil surface. Poorly maintained basins often had several weeds, both actively growing or dead. The basins classified as fair condition often contained healthy, yet overgrown and haphazard plant growth. Roots play an essential role a stormwater basin’s ability to infiltrate runoff (Houdeshel et al., 2013), (Hart et al., 2017). In semi-arid climates, grasses and shrubs develop enormous root networks in shallow soils, three to five times the biomass above ground. Desert grasses demonstrate vertical root growth up to 60 cm in depth, and they “can regrow up to six sets of roots to this depth per growing season” (Houdeshel et al., 2013). If a basin has brushgrasses present, they can routinely create preferential flow paths that quickly drains water through the top soil and maximize stormwater capture.

Native shrubs, such as creosote bush, sagebrush, and velvet mesquite also establish vast root growth. These plants combine dense, shallow root networks with deep tap roots to secure a water supply. Tap roots that grow nearly 5 meters deep have been shown to draw water up from deep, saturated pockets and release moisture in the drier topsoil (Houdeshel et al., 2013). This transported water becomes available to support microbial organisms, shallow grasses, and cools the air through transpiration. This highlights a symbiotic relationship between soil microbiota and plants. Houdeshel et al. (2013) discusses how soil structure and infiltration rates are enhanced by arbuscular mycorrhizal fungi (AMF); the fungi assists with the nutrient absorption for plants in xeric climates. The authors describe a symbiotic relationship between root length and AMP interactions. As bunchgrasses grow a dense cluster of roots, it interacts with AMF to aggregate the surrounding soil and retain soil moisture (Houdeshel et al. 2013). From the observations in this study, it is plausible that poorly maintained basins had more opportunity for unrestricted plant growth and organic matter accumulation, while great condition basins experienced landscaping that removed weeds, grasses, and plant debris. This could explain the consistently higher infiltration rates of poor condition basins compared to well-maintained ones.

VII.I Assumptions

In order to understand the results in the context of this research, some assumptions must be addressed. Soils are notorious for having high heterogeneity, both spatially and temporally. For most basins, only one SCAP measurement was taken. This single measurement means the variability of the GI basins was not assessed. If a basin appeared to have an usually high air flow, the measurement was repeated to verify that the soil core barrel was placed properly, and air was not up leaking up the barrel sides. Figures 8 and 9 illustrate that qualitative assessment categories had a wide range of Ks values. This is a relatively large amount of variability for soils that predominantly had a texture of sandy loam. Another potential concern of this research is the lack of initial conditions. It is unknown what the permeability of the soil was when the GI basins were installed. It is unclear if the construction of the basins caused any soil compaction to occur, or if caliche layers were present in the subsurface. Often, the ground between sidewalks and roadways were bare, but some neighborhoods had plants and weeds growing unabated; the initial soil organic matter was unknown. The current amount of soil organic matter was not directly measured, only qualitatively observed. The actual maintenance involvement from homeowners over the lifetime of the basin is uncertain Given the age of the basins, it is plausible some basins received attention in their early years, until changing residents or disinterest halted upkeep.

Additional assumptions involve the conditions needed for the soil corer air permeameter. Isotropic conditions are necessary for accurate measurements under Darcy's Law; however, in a handful of cases, removing the soil barrel after taking an air flow measurement revealed distinct soil layers. For example, five basins in a row at Feldman's neighborhood had a dark, rich loamy sand, then abruptly changed to a reddish-orange gravel sand 5-6 cm down. Additional SCAP tests a few feet away revealed the same anisotropy. Unavoidable soil horizons may have affected the accuracy of the air flow calculations. Soil moisture was another complicating factor. Some basins were noticeably damp after clearing organic debris, or near the base of the soil core ten centimeters down. To address this, the measurement was either taken another day, or the soil moisture was pushed out by the air tank. At four basins in the Garden District, the air flow was left on for several minutes in an attempt to dry the soil. In these instances, the air flow low to prevent alteration of the soil structure. For three out of the four basins, a linear measurement between three different pressures was obtained, indicting the soil eventually became dry enough.

VIII. Recommendations

If adequate basin drainage of stormwater runoff is the sole criteria for a successful installation, then long-term maintenance may not be necessary at all. Basins with an absence of maintenance, left alone to freely grow weeds, shed leaves, and build up organic litter, consistently had high hydraulic conductivity rates. Organic debris appear to improve soil structure and facilitate increased drainage. Routinely removing this natural build-up of leaf litter and debris could, in fact, inhibit the GI basin's ability to infiltrate stormwater. In the natural environment, the accumulation of dead plant matter is a regular occurrence. Author Pavao-Zuckerman (2008) argues that a healthy soil is an ecological process that develops slowly over time, from countless interactions with weather, plants, topography, and soil minerals. These external factors change the soil structure over time. Urban soils can be inherently cut-off from these normal processes, and the rate of infiltration may suffer as a result (Pavao-Zuckerman 2008). Based on Figure 10c. the clear increase in hydraulic conductivity for basins with a thick layer of organic matter, it is recommended that organic mulch be incorporated in the GI basin design. Neighborhood residents can also be advised to leave the natural build-up of plant debris in place. Mulch serves a variety of purposes, including acting as a filter for fine sediments, dissipating energy from inflowing water, preventing erosion, and retaining soil moisture (US EPA, 2016). Including a layer of mulch over the sandy basin bottom can retain soil moisture for longer periods of time, encouraging microbiota and root growth. Soil with high organic content was found to have significantly increased soil moisture in the first few centimeters (Franzluebbers 2002). The addition of organic matter at the onset of GI basin installation may improve soil structure and infiltration rates over time.

High vegetation density and diversity should be a high priority for GI. Roots of native bunchgrasses and shrub can increase soil stability and generate preferential flow paths. Neighborhoods with basins five to ten years of age are similar to the concept design seen in Figure 3, with one tree and a few small cacti and shrubs. While this design is an adequate approach, this research suggests that basins with a heavy presence of weeds and overgrowth improve basin drainage, allowing basins to harvest more stormwater runoff. In a study on GI infiltration rates in arid and semi-arid climates, increasing vegetation density by three times and using a wide variety of species significantly improved soil structure and nutrient retention (Houdeshel el al. 2013). In the Garden District neighborhood, with basins installed in 2018, each basin only had a single tree planted, with no other vegetation. Two houses had a shrub in their basin; this suggests either the homeowners invested in those plants, or the ten other basins contained shrubs that did not survive the first year. This neighborhood also had a thick layer of wood-chip mulch approximately three to four inches deep at all twelve curb-cut basins. While it appears the City of Tucson has already adapted some GI designs to include a layer of organic mulch, it seems to come at the cost of plant variety. While mulch can encourage soil moisture, micro biota, and aggregate formation, roots can also significantly contribute to macro porosity in soil. The root zone symbiotically interacts with these elements and enhances the effects. Leaving this critical piece out of the equation can limit the basins ability to drain stormwater. Additionally, many of the indirect, long-term benefits of GI are derived from the “green” aspect; vegetation should be fully embraced and treated as the central component to maximize the potential of GI. Based on my observations and the results of this study, it is recommended that dense vegetation be fully incorporated into neighborhood scale GI design.

The infiltration rate of the basin is a critical function. The higher the permeability, the more contaminated-loaded runoff can be diverted and retained from accumulating downstream. However, functionality should not be the only consideration for a GI basin. When the aesthetic value of GI is overlooked, it comes at a price. While collecting measurements with the SCAP, homeowners would frequently come outside and ask about my project. They would comment about their GI basin, and some homeowners discussed how frequently they watered the plants or how often they removed trash. Many times, the homeowners were unhappy with the appearance, commenting that overgrown shrubs and weeds were unsightly. One homeowner stated they wished the curb-cut would be “bricked up” because it was an eyesore. A preference for manicured landscapes is a common issue; residents complain about unruly GI designs near their property, and often “poor maintenance exacerbates these complaints”. (Liptan and Santen, 2017). The aesthetic of the basin was a high priority for the neighborhood residents. This highlights a problem at the community level. There is a lack of understanding of what basins are for, and why they are significant. This is especially an issue if homeowners are expected to routinely remove trash or debris blocking the inlet. The impact of aesthetic value on the longevity of a basin should not be underrated. GI features need management much like “a garden needs tending” (Pincetl, 2013). A basin with dead vegetation that appears to be a roadway mistake detracts from the overall neighborhood appeal, and the GI does not live up to its full intended value. Healthy, dense vegetation would support basin drainage by adding organic matter to the soil, as well as improve the curb-side appeal of a lush landscape. Communication on GI’s role and long-term care techniques may improve plant lifespan and community appreciation.

City planners often want to treat GI as a uniform installation with clear expectations on performance, similar to a pipe or a drainage tank. However, because of the nature of GI benefits, it may be wise to consider these neighborhood stormwater management programs from the vantage point of a social objective. Behavioral insights, such as understanding social norms and motivators, can supplement traditional methods of management by “shaping the behavior of citizens to promote public priorities” (Farrow et al. 2017). Each GI feature requires an indeterminant amount of attention and is built with an expectation of homeowner input to achieve the various indirect benefits, similar to a community garden. The success of sustainable programs like neighborhood GI requires the consideration of “local ecological, political, economic, and social conditions” (Pincetl, 2013). A dynamic system that clearly encourages shared maintenance responsibility between homeowners could prove to be a more effective regulatory policy (Fiorino, 2009). Social sciences have shown that “what other people do and think matters a great deal to individuals,” and a successful community project can benefit from tapping into social norm dynamics (Farrow et al. 2017). Green infrastructure operates as a decentralized water resource, and routine upkeep of the vegetation health could benefit from persistent social management strategies.

Environmental non-profits have been embracing the community management approach. Watershed Management Group and Conserve to Enhance are active in bridging the gap between infrastructure projects and social value. Conserve to Enhance has been involved with helping neighborhoods install GI basins in flood prone streets. In 2018, they offered a new grant application for "site stewardship." The winning community would have a contractor provide community members with training and resources to maintain local GI sites. The grant includes materials such as rakes, shovels, work gloves, mulch, and rocks for volunteer residents to trim plants, dig out weeds, clear sediments traps, remove sediment build-up, replenish mulch, and pick up litter (Conserve2Enhance, 2018). This program serves as an excellent social-building exercise with GI education as its focus, and many basins could benefit from the makeover, albeit at the price of removing organic matter. The labor of raking, pulling weeds, and clearing sediment may be unnecessary in regard to stormwater capture and infiltration; however, the improvement in curb appeal may be worth the effort for homeowners. Unfortunately, the site stewardship and training comes at a high price of $8,000 for the year (Conserve2Enhance, 2018). A far more affordable community-building tactic might be a viable.

Watershed Management Group (WMG) takes another approach. In Feld Davis Park, four curb-cut basins are on the corner of 8th street and Martin Ave, on the edge of the High School Wash. All four basins were classified as fair condition; they had dense, overgrown vegetation with scattered weeds, and a layer dead plant debris. This basins also had high infiltration rates, sizable trees and wildflowers. Within the park, several passive rainwater-harvesting basins - shallow depressions lined with cobblestone rocks and trees- were present A creative aspect of the park are the box libraries placed near seating areas. A sign is posted above the small box library, which describes green infrastructure, the benefits it provides, and the effort to restore a natural wash in an urban setting. A colorful mural is displayed over the park entrance and blue flow lines are painted on the asphalt leading into the basins. This type of integration between social engagement and water-harvesting basins is where green infrastructure can flourish. The sign educates the community and sets expectations on GI basin function. Communication is a critical step of a collective management. With pictures and clear descriptors, WMG provides "objective indicators that the desired results are being achieved" (Fiorino, 2009). When people see how GI basins add value to their community, they are more likely to invest their time into caring for it as if it were their own yards.

I recommend including a library box at every neighborhood GI site. To encourage the dissemination of neighborhood GI, library boxes could be placed next to future GI basins. An informational panel placed on the side of the library box could outline GI purpose, benefits, and simple maintenance requests, such as care for the plants and the removal of trash. When information is readily available and expectations are explicit, homeowners are likely to be more responsive. Furthermore, as neighbors walk to the library box, they can see which residents maintain their basins and which do not. This can generate a competitiveness between neighbors who hold landscaped yards in high regard. Residents are more receptive to water management if mechanisms exist for accountability (Lund, 2015). Library boxes are an affordable and inclusive mechanism for GI maintenance. The GI basins can cost anywhere between $1,124 and $4,000 per bioswale and curb-cut ("Triple Bottom Line", 2018). Pre-made library boxes cost between $250 - $350 ("Little Free Libraries", 2018). Little Free Library is community improvement non-profit with resources for anyone to install their own neighborhood library. Walking to and from a neighborhood library box can add maintenance accountability when neighbors are aware of GI purpose and can compare basin conditions themselves.

The library boxes also offer a permanent educational resource. Instead of workshops, pamphlets, or stewardship grants, the little libraries can showcase GI education for several years. They can be placed once, with little oversight or upkeep, and remain a facet in the community. If renters or homeowners eventually move away, the community libraries will still be situated for the education of new residents. If neighborhood GI is expected to function for five decades, extended management plans are critical. Collaborative management is often employed to handle long-term environmental issues. Unless these collective, educational resource are supported over many years, they may be unsuccessful at achieving desired goals. However, "if collaborative networks are sustained over time, they can lead to the cultivation of common norms (Bodin, 2017). Communication and persistence are among the key elements of successful collective management strategies (Lund, 2015).

When it comes to maintaining both the aesthetic and function of green infrastructure, "decentralized management institutions are often more flexible, responsive, and accountable than centralized governmental institutions" (Lund, 2015). When an appropriate social framework is fostered alongside GI implementation and residents are active in basin care, city planners can lean into the "green" aspect of green infrastructure by including more vegetation. Trees and shrubs are often the least expensive part of the project ("Triple Bottom Line", 2018). Planting more native vegetation increases the likelihood of building up a natural mulch layer. Organic matter and shallow roots in the soil matrix can increase permeability, and theoretically improve drainage over time. The urban tree canopy gets attention as an attractive externality of GI. However, several basins I visited were missing trees, suggesting they died before maturity. This severely undercuts the potential of GI and the goals of reducing urban heat island effect. Even if a tree survives the first three years, many GI basins in a range of conditions show limited vegetation. Native bushes and shrubs can also provide valuable transpiration cooling, in addition to the habitat cover for desert wildlife. With the right residents motivated to care for GI, the City of Tucson can embrace lush, dense curb-cut basins. To support the other positive externalities of GI, it is recommended that the distribution of GI education and volunteer maintenance information should be incorporated into the City of Tucson's long-term planning.

IX. Conclusion

This research analyzed how maintenance may influence the function of neighborhood scale, stormwater harvesting, curb-cut basins. It began with theory that maintenance is necessary for neighborhood green infrastructure basins, and basins that appeared well cared for would demonstrate higher infiltration rates. The results found that maintenance may not be needed for the effective drainage of a basin. After studying 88 GI basins in five different Tucson neighborhoods, basins that appeared to have an absence of maintenance consistently demonstrated higher hydraulic conductivities. The increase in infiltration rates corresponded to basins with a thick layer of organic matter, suggesting that soil organic matter influences permeability. The basins that appeared poorly maintained also seemed to generate dissatisfaction with residents. This suggests some additional community outreach on basin care may be necessary for the long-term success of neighborhood curb-cut GI.

The value of green spaces in urban areas should not be underestimated. Green infrastructure allows cities to tap into the sustainable resource of urban runoff. Communities around the U.S. are “beginning to use stormwater as a resource, recognizing the value in utilizing rainfall on site to enhance green spaces, reduce urban temperatures, and replenish groundwater supplies" (Liptan & Santen, 2017). Allowing organic matter to build up in the soil can support soil biota that fundamentally change soil structure and porosity to facilitate better air and water flow. This improves the basin function for capturing and infiltrating rain water, as well as a healthier environment for vegetation. (Elliot and Coleman, 1988). If cities want to maximize the benefits of GI, the vegetation component should be given more weight and priority. All the benefits commonly listed for Tucson green infrastructure programs, such as cooling sidewalks and buildings, improving air quality, increasing property values, encouraging recreation, come from a GI design with heathy plants and large tree canopies. This is difficult for Tucson’s Department of Transportation to handle on their own; the agency is not built for widespread landscape monitoring. Neighborhood residents, who regularly encounter the GI basins, can take appropriate measures if the inlets are clogged, trash builds up, or vegetation is struggling. Currently, many neighborhood residents seem unaware of the purpose of neighborhood GI basins, let alone their role in maintaining them. More educational outreach and social incentives to homeowners could improve the community’s relationship with GI. Encouraging resident participation in the management of GI could improve the vegetation health and enhance the overall function of curb-cut basins.

IX.I Future work

Going forward, this research can be extended in many ways. More measurements of infiltration rate should be taken at each basin, and the number of basins classified under each condition should be expanded. Ideally, the sample size within each category would be greater than thirty for robust results. The preliminary results of this research can be corroborated with a wider sample selection of curb-cut basins from several neighborhoods around Tucson. Additionally, this research would do well on a time frame of two -five years. Comparing a temporal change in infiltration rate for the basin may shine light of their design performance. Commercial rainwater-harvesting GI can also be valued and compared. This research can also be expanded by continuing to investigate the role of soil biota and mulch on infiltration rate. A substantive evaluation of microorganism composition, density, or respiration in the basin soil would be essential for understanding the exact role it plays on soil structure and preferential flow paths. The type, thickness, and composition of the organic mulch litter would help define the optimal use. Surveys sent to homeowners could assess the current social engagement in neighborhoods with GI. There is still much work to be done before green infrastructure designs are perfected. However, researchers continuously strive to find better practices, so that we many increase the benefits for society. Sustainable stormwater harvesting in Tucson is here to stay.

X. References

Ahiablame, Laurent, M. Engel, and B. Chaubey. "Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research." *Water, Air, & Soil Pollution* 223.7 (2012): 4253-273.

Bodin, Örjan. "Collaborative Environmental Governance: Achieving Collective Action in Social-ecological Systems." *Science*, Aug 18, 2017, Vol.357(6352).

Bronick, C. J., and R. Lal. "Soil Structure and Management: A Review." Geoderma, vol. 124, no. 1, 2005, pp. 3-22.

Canfield, Evan. "Stormwater in Pima County – a Blessing and a Curse." *Pima County Flood Control*, Stormwater Summit, Mar. 2017.

Chief, Karletta, et al. "Field Testing of a Soil Corer Air Permeameter (SCAP) in Desert Soils." *Vadose Zone Journal*, vol. 5, 20 Nov. 2006, pp. 1257–1263., doi:10.2136/vzj2006.0063.

Chief, Karletta. "Soil Air Permeability and Saturated Hydraulic Conductivity: Development of Soil Corer Air Permeameter, Post-Fire Soil Physical Changes, and 3D Air Flow Model in Anisotropic Soils." *University of Arizona*, 2007, pp. 1–205. UA Repository, hdl.handle.net/10150/195482.

Conserve2Enhance, "Grants for New Sites." *Water Resource Research Center*, University of Ariozna, 2018, conserve2enhance.org/program/grants.

Cook, Michael. "Improving Green Infrastructure." *Ohio Water Environment Association*, 18 May 2016.

Coutts, Christopher, and M. Hahn. "Green Infrastructure, Ecosystem Services, and Human Health." *International Journal of Environmental Research and Public Health*, vol. 12, 2015, pp. 9768–9798., doi:10.3390/ijerph120809768.

Elliott, E. T., and D. C. Coleman. "Let the Soil Work for Us." *Ecological Bulletins*, no. 39, 1988, pp. 23-32

Farrow, Grolleau, and Ibanez. "Social Norms and Pro-environmental Behavior: A Review of the Evidence." *Ecological Economics*, 140, 2017, 1-13.

Feehan, Caitlin. "A Survey of Green Infrastructure Maintenance Programs in the United States." Hixon Fellowship, *Yale School of Forestry and Environmental Studies*. 2013, pp. 1–21.

Fiorino, Daniel. "Regulating for the Future: A New Approach for Environmental Governance." *Toward Sustainable Communities: Transition and Transformations in Environmental Policy*, by Daniel Mazmanian and Michael Kraft, MIT Press, 2009, pp. 63–86.

"Green Streets Active Practice Guide, Tucson, Arizona." Naturally Resilient Communities, *The Kresge Foundation*, nrcsolutions.org/green-streets-active-practice-guide-tucson-arizona/.

Hart, Ted, J. Yeakley, A. Latimer, J. Maser, and T. Rosenstiel. "Root-enhanced Infiltration in Stormwater Bioretention Facilities in Portland, Oregon" *Portland State University*, Environmental Sciences and Resources. 2017.

Head, K. H.. "Manual of soil laboratory testing" *Pentech Press*, 1982, ISBN 0-7273-1305-3

Hinds, Juli, and M. Beezhold. "The Framework of Regulations, Standards, and Structures." Green Infrastructure Implementation, *Water Environment Federation*, 2014, pp.53–66.

Houdeshel, Christopher, C. Pomeroy, D. Bowling, S. Burian, R. Goel, and K. Hultine. "Adapting Bioretention for Stormwater Treatment in Xeric Climates." *University of Utah*, Department of Civil and Environmental Engineering. 2013.

Hufnagel, Carol, and N. Rattle. "A Historical Perspective of Green Infrastructure." Green Infrastructure Implementation, *Water Environment Federation*, 2014, pp.4-11.

Impact Infrastructure, LLC, and Santec. “Evaluation of GI/LID Benefits in the Pima County Environment.” Pima County Regional Flood Control District, *Pima Association of Governments, & the City of Tucson*, 2014, pp. 1-90.

Jalbert, M., and J.H. Dane. “A handheld device for intrusive and nonintrusive field measurements of air permeability.” *Vadose Zone*, 2003. V.2 pp.611-617.

“Little Free Libraries on a Shoestring Budget.” *Little Free Library - Take a Book, Share a Book*, 11 June 2018, littlefreelibrary.org/little-free-libraries-shoestring-budget/.

Liptan, Thomas, and J. Santen Jr. “Economics, Policy and Polictics: Preparing for Landscape Stormwater Management.” *Sustainable Stormwater Management*, 2017. pp.45-65.

Loll, P., P. Moldrup, P. Schjønning, and H. Riley. “Predicting saturated hydraulic conductivity from air permeability: Application in stochastic water infiltration modeling.” *Water Resource Research*, 1999. v.35 pp. 2387-2400.

Lund, Jay. “Integrating social and physical sciences in water management.” *Water Resource Research*, 2015, 51, 5905– 5918, doi:10.1002/2015WR017125.

MacAdam, James. “Green Infrastructure for Southwestern Neighborhoods.” *Watershed Management Group*, Oct. 2012, www.watershedmg.org/green-streets

Morales, Verónica, J. Parlange, and T. Steenhuis. "Are Preferential Flow Paths Perpetuated by Microbial Activity in the Soil Matrix? A Review." *Journal of Hydrology*, 2010, vol. 393, pp. 29-36.

“Operations and Maintenance.” *Seattle Public Utilities*, Seattle.gov, www.seattle.gov/util/EnvironmentConservation/Projects/GreenStormwaterInfrastructure/CompletedGSIProjects/OperationsMaintenance/index.htm.

Matsuno, Hiroko, and Selina Chiu. “SEA Streets – The Stormwater Management Challenge.” *Seattle Public Utilities*, Seattle.gov, Winter 2010, pp. 1-8.

Pavao-Zuckerman, Mitchell. "The Nature of Urban Soils and Their Role in Ecological Restoration in Cities." *Restoration Ecology*, vol. 16, no. 4, Dec. 2008, pp. 642–649., doi:10.1111/j.1526-100X.2008.00486.x.

Pennypacker Eliza. "The History of Stormwater Management and Background for Artful Rainwater Design." *Artful Rainwater Design: Creative Ways to Manage Stormwater*, Island Press, 2015, pp. 7–22.

Pincetl, Stephanie. "Urban Ecology and Nature's Services Infrastructure: Policy Implications of the Million Trees Initiative of the City of Los Angeles." *Urbanization and Sustainability: Linking Urban Ecology, Environmental Justice and Global Environmental Change*, 2013, pp. 61–74.

"Triple Bottom Line: Cost Benefit Analysis of Green Infrastructure/Low Impact Development (GI/LID) in Phoenix, AZ" *City of Phoenix*, 21 Jun. 2018, https://www.phoenix.gov/oepsite/Documents/City%20of%20Phoenix_GI%20and%20LID_TBL-CBA%20Autocase%20Features%20and%20Projects%20Evaluation_06-21-2018.pdf

Tucson Clean and Beautiful, Inc. "Neighborhood Scale Stormwater Harvesting Program." *Pima County, City of Tucson, Arizona.* May 2017, tucsoncleanandbeautiful.org/trees-for-tucson/neighborhood-stormwater-harvesting/.

United States, Environmental Protection Agency, "Green Infrastructure for Stormwater Control: Gauging Its Effectiveness with Community Partners." *Office of Research and Development*. Oct. 2016, pp. 1–58. www2.epa.gov/water-research.

United States, Environmental Protection Agency, "Operation and Maintenance of Green Infrastructure Receiving Runoff from Roads and Parking Lots." *Tetra Tech Inc, Great Lakes National Program Office,* Sep. 2016, pp. 1–23.

Wittwer, Gary. "Greet Streets - Active Practices Guidelines." *City of Tucson, Arizona*, Department of Transportation, Engineering Division, Aug. 2013.

Weeks, E.P. “Field determination of vertical permeability to air in the unsaturated zone.” *U.S. Geological Survey*, Paper 1051, 1978, US Gov.

Wright, Sara, and A. Upadhyaya. "Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of Arbuscular Mycorrhizal Fungi.” *Soil Science* 161.9, 1996, 575-86.